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Metacontrol of human creativity: The neurocognitive mechanisms of convergent and divergent thinking

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A B S T R A C T

Creativity is a complex construct that would benefit from a more comprehensive mechanistic approach. Two processes have been defined to be central to creative cognition: divergent and convergent thinking. These two processes are most often studied using the Alternate Uses Test (heavily relying on divergent thinking), and the Remote Associates Test (heavily relying on convergent thinking, at least with analytical solutions). Although creative acts should be regarded compound processes, most behavioral and neuroimaging studies ignore the composition of basic operations relevant for the task they investigate. In order to provide leverage for a more mechanistic, and eventually even comprehensive computational, approach to creative cognition, we compare findings from divergent and convergent thinking studies and review the similarities and differences between the two underlying types of processes, from a neurocognitive perspective with a strong focus on cortical structures. In this narrative review, we discuss a broad scope of neural correlates of divergent and convergent thinking. We provide a first step towards theoretical integration, by suggesting that creative cognition in divergent- and convergent-thinking heavy tasks is modulated by metacontrol states, where divergent thinking and insight solutions in convergent-thinking tasks seem to benefit from metacontrol biases towards flexibility, whereas convergent, analytical thinking seems to benefit from metacontrol biases towards persistence. These particular biases seem to be reflected by specific cortical brain-activation patterns, involving left frontal and right temporal/parietal networks. Our tentative framework could serve as a first proxy to guide neuroscientific creativity research into assessing more mechanistic details of human creative cognition.

1. Introduction

Creativity is a mysterious and complex phenomenon thought to be capital of the human mind. It has shown to be hard to objectify and quantify, which has hampered mechanistic approaches of creativity. Yet, despite its complexity, it can be seen as an ability requiring both originality and effectiveness (Runco and Jaeger, 2012). The construct of creativity is thought to comprise two measurable cognitive ingredients that are crucial to the creative processes everyone experiences on a daily basis: divergent and convergent thinking (Guilford, 1967). Divergent thinking represents a style of thinking that allows idea generation, in a context where the selection criteria are relatively vague and more than one solution is correct. Divergent thinking, therefore, involves flexibility of the mind. In contrast, convergent thinking represents a style of thinking that allows finding single solutions to a well-defined problem, which requires more persistence and focus (Guilford, 1950; Runco, 2010). Interestingly, one could potentially distinguish the two processes in earlier models on stages of creative processes. For example, almost a century ago, Wallas (1926) suggested that creative acts run through four stages including (1) preparation: the problem is investigated; (2) incubation: the problem is thought about unconsciously; (3) illumination: ideas come together to form a possible solution; and (4) verification: the chosen option is evaluated. It makes sense to characterize the first two stages as relying more on divergent thinking and the last two stages as relying more on convergent thinking.

Considering the different characteristics of divergent and convergent thinking and the different roles they play at the stages of creative production, it makes sense to assume that the two thinking styles rely on different functional and neural mechanisms (Akbari Chermahini and Hommel, 2010; Dreisbach and Goschke, 2004). Unfortunately, however, research on creativity has often considered creativity as one coherent concept that relies on one coherent ability that can be assessed by means of comprehensive, unitary questionnaires or tasks that lump together separable, presumably rather different components—which does not seem to do sufficient justice to the underlying mechanics. Even studies that did not equate the two thinking styles have focused exclusively on either divergent tasks (for overviews and discussion, see Baas et al., 2008; Davis, 2009) or convergent tasks (e.g., Isen et al., 1987), providing a rather fragmented, non-comprehensive view on creativity mechanisms. And yet, multiple findings support the assumption of critical differences between divergent and convergent thinking. In particular, divergent and convergent thinking could be demonstrated to be (1) inducing different,

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or even opposite, mood states (Akbari Chermahini and Hommel, 2012a); (2) associated with different metacontrol states (Hommel, 2015); (3) differently related to the neuromodulatory dopamine system in the brain (Akbari Chermahini and Hommel, 2010); and (4) differently influenced by behavioral interventions such as meditation (Colzato et al., 2012; Colzato et al., 2014).

Even though these and other observations point to important differences between divergent and convergent thinking, there are also some indications of similarities. For instance, whereas individual measures of performance in divergent and convergent thinking tasks have been reported to be uncorrelated in a study of European participants (Akbari Chermahini and Hommel, 2010), significant positive correlations between the two measurements were found in Chinese participants (Shen et al., 2018a,b). Moreover, a recent explorative open-label study on microdosing psilocybin, known to influence serotonin receptors in the brain, indicated that both divergent and convergent thinking processes improve after taking microdoses of psilocybin (Prochazkova et al., 2018). Similarly, it was found that convergent and divergent thinking do share similarities in neural patterns, especially in increased alpha band activity as measured with electroencephalography (EEG) (Jung-Beeman et al., 2004; Fink et al., 2009a, 2009b).

To summarize, divergent and convergent thinking are subcomponents of creativity that show both similarities and differences that are far from being understood (Mekern et al., 2019a; Sternberg et al., 2013). The current, subcomponent-indifferent approach, and the lack of understanding on differences and similarities between the two, severely limits our opportunities to systematically study and effectively enhance human creativity. The purpose of the present narrative review is to provide an overview and a theoretical integration of what is known in the literature about similarities and differences between convergent and divergent thinking. We see this as an important first step, before looking further into more detailed computational processes that could more readily be connected to neural correlates, and further improve our knowledge on creative mechanisms. We will discuss the similarities and differences between divergent and convergent thinking in the context of both behavioral and neuroimaging findings, to give further leverage to studying and understanding more detailed underlying neurocognitive mechanisms of the complex construct of creativity. The theoretical integration that we suggest is based on the assumption that divergent and convergent thinking rely on systematic differences in the underlying metacontrol state (Hommel, 2015), that is, on the general information-processing mode that the thinking individual establishes in order to carry out divergent- or convergent-thinking tasks. In the following, we will first explain what a metacontrol state is and how it may relate to divergent and convergent thinking in terms of functional characteristics, neuromodulation, and brain areas involved. Then we will briefly discuss how divergent and convergent thinking can be measured, and on which particular tasks our review will focus, before we review the behavioral and cortical neuronal key findings related to divergent and convergent thinking.

1.1. Metacontrol of divergent and convergent thinking

Given that divergent and convergent thinking are likely to serve different purposes and to satisfy different task demands, it is important to characterize these two thinking styles in more detail. To account for these differences, the Dual Pathway to Creativity (DPC) Model (Nijstad et al., 2010) has been proposed. The model distinguishes between a flexibility route and a persistence route to creative performance, and it assumes that creative products and even different measures in the same creativity task may rely on these two routes to different degrees. To create a highly original idea or product, flexibility is needed to switch between different and remote associations to find a better idea or solution (Vartanian, 2009), but persistence is also required to focus on the task at hand and to find the final solution (De Dreu et al., 2012). The two routes can thus be assumed to collaborate differently in divergent and convergent thinking: the flexibility route may dominate in divergent thinking, and in particular when switching between different categories, whereas the persistence route may dominate in convergent thinking or in producing different items of the same category in divergent thinking (Fig. 1).

The idea that behavior emerges from a balance between persistence and flexibility is also key in the Metacontrol State Model (MSM; Hommel, 2015), a model that was conceived to account for cognitive control in general, but that can be easily applied to creativity and convergent and divergent thinking as well. The MSM is used to describe the balance between persistence and flexibility in any kind of decision-making, which the model assumes (following Bogacz, 2007) to be competitive (winner-takes-all) and biased according to currently active goals (see competition and top-down bias in Fig. 2, respectively). If, thus, two or more goal-related representations compete for selection (indicated by mutual inhibition), increases in activation of a better alternative reduces the activation of the other. The degree to which alternatives compete and to which they are biased by current goals is determined by the present metacontrol state, which varies between persistence and flexibility. Extreme persistence would consist in strong mutual competition as well as top-down bias, whereas extreme flexibility would consist in weak competition and weak top-down bias. Accordingly, convergent thinking would be expected to rely on, or at least benefit from, a bias towards persistence, whereas divergent thinking should rely on, or benefit from, a bias towards flexibility (Hommel, 2015; Hommel and Colzato, 2017b; Mekern et al., 2019b).

The DPC and the MSM models differ in focus and emphasis, but they are highly consistent for the most part and both relate to dopaminergic activity. In particular, striatal dopamine and the integrity of the nigrostriatal dopamine pathway have been assumed to be associated with flexible processing, and prefrontal dopamine and the integrity of the mesocortical dopaminergic pathway with persistent processing (Boot et al., 2017a,b; Hommel and Colzato, 2017b).

Empirical findings support the idea that divergent and convergent thinking are related to flexibility and persistence, respectively. The link between divergent thinking and cognitive flexibility receives support from the observation that positive mood, which is assumed to support flexibility (Baas et al., 2008; Akbari Chermahini and Hommel, 2012a; Ritter and Ferguson, 2017), was shown to promote “loose thinking” and creative thought (Ashby and Isen, 1999; Baas et al., 2008), and engaging in divergent thinking introduces more positive mood states (Akbari Chermahini and Hommel, 2012a). Along the same lines, spontaneous eyeblink rates, which are assumed to be a marker of the striatal dopamine level (Jongkees and Colzato, 2016)—the dopaminergic pathway that cognitive flexibility is assumed to rely on (Klanker et al., 2013) —predict

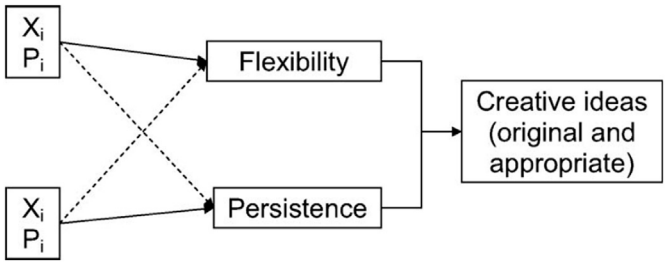

Fig. 1. The dual pathway to creativity model according to Nijstad et al. (2010). There are two pathways to achieve creativity: a flexibility and a persistence pathway, and both pathways are influenced by situational (denoted with Xi) and dispositional (denoted with Pi) factors. However, some situational and dispositional variables affect the flexibility pathway more strongly than the persistence pathway, and vice versa, which is indicated by solid (stronger relation) and dotted (weaker or negative relation) lines, respectively. Reprinted without changes, with permission from Taylor and Francis (www.tandfonline.com), based on Fig. 1 from Nijstad et al. (2010) The dual pathway to creativity model: Creative ideation as a function of flexibility and persistence, European Review of Social Psychology, 21:1, 34–77.

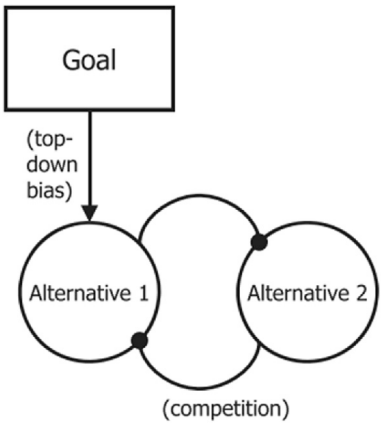

Fig. 2. Key assumptions of the Metacontrol State Model according to Hommel (2015)**.** Metacontrol flexibility states are characterized by the strength of top-down guidance from goal representations for goal-consistent selection candidates and the strength of mutual competition for alternative selection candidates. Flexibility is implemented through weak top-down guidance and mutual competition, whereas persistence is characterized by strong top-down guidance and mutual competition. Reprinted without changes, with permission from Elsevier based on Fig. 1a from Hommel (2015) Between persistence and flexibility: The Yin and Yang of action control. In: A.J. Elliot (ed.), Advances in motivation science, Vol. 2 (pp. 33–67). New York: Elsevier.

individual performance in divergent thinking (Akbari Chermahini and Hommel, 2010). This in turn fits with the observation that inducing positive mood increases both spontaneous eyeblink rates and divergent-thinking performance (Akbari Chermahini and Hommel, 2012b). Analogously, divergent thinking benefits from engaging in open-monitoring meditation, which has been assumed to induce more flexible metacontrol states (Hommel and Colzato, 2017a). Conversely, engaging in divergent thinking was shown to affect performance in ways that have been assumed to reflect a metacontrol bias towards flexibility (Hommel and Colzato, 2017a), such as more integrating bystanders into one's self-representation (Colzato et al., 2013) or increasing interpersonal trust (Sellaro et al., 2014).

In addition, spontaneous mind wandering (Baird et al., 2012) and decreased latent inhibition (Carson et al., 2003) have been related to flexible cognition (Mason et al., 2007; Nonkes et al., 2012; Ottaviani et al., 2013) and seem to facilitate divergent thinking. Subclinical symptoms of attention-deficit/hyperactivity disorder (ADHD), a disorder associated with high impulsivity and flexibility (Colomer et al., 2017; Sinzig et al., 2008), were also found to be associated with enhanced divergent thinking (Boot et al., 2017a,b). Moreover, the personality traits openness and extraversion are selectively correlated with divergent thinking, but not convergent thinking (Chamorro-Premuzic and Reichenbacher, 2008)—thus also suggesting a dissociation.

Other findings provide support for a link between convergent thinking and cognitive persistence. For instance, working memory performance, which is related to executive function and involvement of the prefrontal cortex, could predict convergent thinking but not divergent thinking (Lee and Therriault, 2013). Moreover, engaging in convergent thinking was found to induce negative mood (Akbari Chermahini and Hommel, 2012a), which in turn is suspected to narrowing the focus of attention (Rowe et al., 2007); but see Bruyneel et al., 2013). Along similar lines, convergent thinking benefits from focused-attention meditation, which is assumed to induce a metacontrol bias towards persistence (Colzato et al., 2012), and from bilingualism, which is expected to do the same (Hommel et al., 2011). In addition, engaging in convergent thinking task was found to increase top-down control and reduce cross-talk in dual-task performance (Fischer and Hommel, 2012).

2. Neuromodulation of metacontrol

The emphasis of both the DPC model and the MSM on dopamine was fueled by, and received support from numerous findings from research on the impact of neurotransmitters on cognitive control (see the recent reviews by Boot et al., 2017a,b, and Hommel and Colzato, 2017b, which we briefly summarize here). In a nutshell, there is increasing evidence from neuroscientific analyses and behavioral genetics that creative cognition is a function of dopaminergic modulation in fronto-striatal brain circuitries, and that persistence as well as flexibility in creative cognition are modulated by prefrontal dopamine and striatal dopamine, respectively. More specifically, findings suggest that the mesocortical dopaminergic pathway that originates in the ventral tegmental area (VTA) and innervates the prefrontal cortex (Goldman-Rakic, 1992), is fueling cognitive persistence. It is less clear whether this is because the mesocortical dopaminergic pathway is driving prefrontal cortex as a whole (e.g. Cools, 2008) or whether it mainly drives dopaminergic D1 family receptors that dominate, but are not restricted to prefrontal cortex (Durstewitz and Seamans, 2008). The same logic applies to the striatal dopaminergic pathway that originates in the Substantia Nigra and was found to promote cognitive flexibility: this may be because the pathway drive striatal processing as a whole or because it drives dopaminergic D2 family receptors that dominate, but are not restricted to the striatum

This share of labor is consistent with findings from behavioral genetics, which show that individuals with a genetic predisposition for particularly efficient dopaminergic processing in prefrontal areas excel in persistence-heavy tasks whereas individuals with a genetic predisposition for efficient dopaminergic processing in the striatum excel in flexibility-heavy tasks (Hommel and Colzato, 2017b). Interestingly, the efficiency of dopaminergic processing in prefrontal and striatal areas do not seem to follow a linear function (for a review, see Goldman-Rakic et al., 2000). For instance, Akbari Chermahini and Hommel (2010) observed that the best performance in divergent thinking was associated with medium spontaneous blinking rates—a clinical marker of striatal dopamine (Karson et al., 1983; Taylor et al., 1999). These and other findings suggest that moderate levels of prefrontal and striatal dopamine could facilitate cognitive persistence and flexibility, respectively—suggesting an inverted U-shape function linking dopamine levels to performance (Akbari Chermahini and Hommel, 2010, 2012b; Boot et al., 2017a,b).

In addition to dopamine, one may speculate that norepinephrine might also play a role in regulating human creativity. More specifically, the locus coeruleus-norepinephrine (LC-NE) neuromodulatory system has been proposed to regulate the balance between exploitation and exploration (Beversdorf, 2019; Lin and Vartanian, 2018), a trade-off which shares many characteristics with the opposition between persistence and flexibility. However, at this point the role of norepinephrine is much less clear than that of dopamine.

Taken altogether, the available evidence strongly suggests that frontal and striatal dopaminergic pathways play an important role in human creativity by regulating cognitive persistence and flexibility. However, we currently know much more about the neurotransmitters that are driving creative processes through metacontrol than about the cortical structures that are being driven by them. To improve this situation, we asked, in the case of dopamine, and perhaps noradrenaline, are the fuel of regulating creativity, which areas are fueled by them? After a brief discussion of the conceptual distinction between convergent and divergent thinking, and their possible relationship to metacontrol, we will thus consider which cortical structures might be involved in regulating human creativity, possibly through metacontrol states, and how they might interact in order to achieve that. We will put our focus on cortical correlates, and not subcortical areas, as most of our claims are supported by (surface-based) EEG studies.

2.1. Assessing divergent and convergent thinking

Divergent thinking represents a type of thinking that allows many new ideas being generated, in a context where more than one solution is correct. Guilford's (1967) *Alternative Uses Task* (AUT) is currently most used to measure people's divergent thinking ability: participants are presented with a particular object, such as a brick, and they are to generate as many different uses of this object as possible. Classically, four indicators are used to evaluate AUT performance: fluency (the total number of ideas generated); flexibility (the number of categories or themes used by the participants); elaboration (the amount of detail provided); and originality (the extent to which responses are unique compared to the rest of the sample, or population). Note that these four measures assess different aspects of the performance and they differ in theoretical transparency. Fluency and elaboration are not particularly specific to creativity (e.g., fluency will be high for participants who repeat similar versions of the same concept over and over again), and likely to be particularly sensitive to the participant's general vocabulary and motivation. Originality, in contrast, is essential for creativity (Runco and Jaeger, 2012), but this measure has the disadvantage of being dependent on the particular sample: uniqueness is commonly assessed with respect to the current sample under analysis, so that the same performance of a given individual would count less if he or she would happen to have particularly original fellow participants, an issue that classically arises when studying 'creative' populations such as artists. This leaves flexibility as the theoretically most transparent measure, as it qualifies sheer production, by dividing the amount of generated ideas through the number of different categories being used.

A task such as the AUT would be expected to require rather weak top-down support, as the search criterion is rather vague, and given that many answers are possible and correct, the competition between alternatives should also be weak. This means that performance in this task would strongly benefit from a control mode that is biased towards flexibility (Hommel, 2015). This also holds for other tasks that have been employed to assess divergent thinking, such as creative story writing (Martindale and Hasenfus, 1978), thinking of unique consequences of a hypothetical situation (Mölle et al., 1999), a question about how to measure the length of poisonous snakes (Fink et al., 2009a, 2009b), and unusual problems requiring creative solutions (Fink et al., 2006). However, in this review, we mainly focus on the AUT as a central measure of divergent thinking.

Convergent thinking is considered a process of generating one possible solution to a particular, well-defined problem. Mednick's (1967) *Remote Associates Test* (RAT) fits this profile, and is therefore most commonly used in the convergent thinking literature: participants are presented with three unrelated words, such as "cocktail," "dress," and "birthday," and are to identify the common associate ("party"). The total number of correct answers is used to evaluate one's convergent thinking level. This task provides more and rather tight top-down constraints, and there is only one possible answer per item, suggesting that the task calls for a control state with a strong impact of the goal —a bias toward persistence (Hommel, 2015). Compared with other convergent tasks like color categorization (Gibson et al., 2009), color matching task (Folley and Park, 2005), word ends task (Fink et al., 2009a, 2009b), and mental arithmetic (Razoumnikova, 2000), RAT is thought to involve more creativity-specific processes (Gabora, 2018). The RAT requires participants to hold one target word as a primary cue and to subsequently think of other related associations. Therefore, it is likely that, in contrast to what is commonly assumed, the RAT might also involve aspects of divergent thinking and, thus, benefit from some degree of flexibility (Olteţeanu and Falomir, 2015). In this review, we mainly focus on the RAT as the measurement used for convergent thinking.

A recent methodological innovation concerning the RAT has been introduced by Kounios and Beeman (2014), who distinguish between solutions that are (according to self-report) found through analytical search and solutions found through spontaneous insight. In contrast to the often step-wise analytical search (also called 'non-insight'), that can be compared to hypothesis testing, insight solutions are experienced as sudden changes in the knowledge representation, leading to a more 'spontaneous' solution of a problem accompanied by a burst of emotion including highly positive surprise (Jung-Beeman et al., 2004; Kounios and Beeman, 2014). Given that finding solutions through insight is often accompanied by a certain lack of focus, it stands to reason that the process underlying insight is more similar to divergent thinking than analytical search would be. Indeed, neural evidence showed that insight solutions do share similarities with the divergent thinking process. For example, in the RAT, during the preparation periods followed by insight solutions, alpha synchronization is seen in the right hemisphere, which is similar to neural patterns seen in divergent thinking, whereas analytical solutions during the RAT were associated with alpha desynchronization (Jung-Beeman et al., 2004; Runco and Yoruk, 2014). However, this regards the preparation period, and it is so far not yet fully understood how the actual finding of insight solution relates to divergent thinking as assessed by the AUT, and thus more empirical evidence is needed.

In any case, these characterizations of divergent and convergent thinking, and the measures used to assess them, reveal that neither AUT nor RAT can be assumed to represent process-pure measures of divergent and convergent thinking or the underlying processes (cf., Nijstad et al., 2010). While it is certainly true that the AUT requires more divergent thinking than the RAT, which in turn requires more convergent thinking than the AUT, we need to keep in mind that in both tasks participants are required to hold one goal-related concept while switching between other possible or actual alternatives (Mekern et al., 2019a). Therefore, the two tasks, as well as the alternatives that have been used, are likely to overlap to a substantial degree and need both divergent and convergent thinking and, thus, both flexibility and persistence (Nijstad et al., 2010). One way to better disentangle divergent and convergent thinking is to better characterize and identify the functional and neural mechanisms underlying these processes, to which we will now turn.

2.2. Neural correlates of divergent and convergent thinking

In recent years, a couple of articles have provided reviews regarding some neuroscientific aspects of creativity in general or divergent or convergent thinking in particular, some with an emphasis on the neural structures being involved (e.g., Dietrich and Kanso, 2010; Kounios and Beeman, 2014; Runco and Yoruk, 2014) and some with an emphasis on the neurochemical underpinnings (Boot et al., 2017a,b; Hommel and Colzato, 2017b). Functional patterns, either during rest or task behavior have provided information on the neurocognitive correlates to creativity, that might refer back to possible connections with metacontrol of cognition. For example, creativity benefits from the interaction or coupling of the executive control network (ECN) and the default network (DN), which reflects both goal-directed episodic memory retrieval and prepotent-response inhibition of semantic information (Beaty et al., 2019), related to persistent cognitive control. The ECN includes lateral prefrontal and anterior inferior parietal regions and the DN is composed by a set of midline and posterior inferior parietal regions (Beaty et al., 2019), thus all areas potentially involved in creativity through their role in metacontrol cognition.

With respect to the neural aspects that we will focus on in the following, three cortical areas have repeatedly been indicated in variants of divergent- and/or convergent-thinking performance: the left inferior frontal gyrus (IFG), the left dorsolateral prefrontal cortex (DLPFC), and overall the right hemisphere, with the posterior parietal cortex (PPC) and closely related areas in particular. Highlighting these areas involved in divergent and convergent thinking implies a discrete localization point-of-view, attributing compound cognitive constructs such as 'convergent' and 'divergent' thinking to discrete topographical brain 'areas'. Although this point-of-view is outdated, it is still adopted in the bulk of the neurocognitive literature, including much of the literature we review here. We will attempt to overcome this, by connecting subprocesses to

activation patterns in these areas, and by providing a theoretical integration of the broader neural circuits that might work together to generate divergent and convergent behavior. As we will argue in the following sections, the degree of activation of left IFG and DLPFC, and the alpha power related to the right PPC and related areas seem to be systematically related to the different types of creative thinking (divergent and convergent), suggesting that a broad network with these three areas as core cortical hubs serves to implement different metacontrol policies.

2.3. Left inferior frontal gyrus (IFG) and left dorsolateral prefrontal cortex (DLPFC)

The left IFG has been found activated both in the AUT and during insight trials of the RAT in fMRI studies. Activation of the left IFG was also found during other divergent thinking tasks, such as generating words from a single letter (Badzakova-Trajkov et al., 2011), creating a book cover from description (Ellamil et al., 2012), brainstorming (Shah et al., 2013), in the Object Characteristics Task, the Name Invention Task and the Word Ends Task (Fink et al., 2009a, 2009b). During the AUT, the left IFG has been found more active than in control tasks, like an object location task or an n-back task (Abraham et al., 2012), or during mere retrieval of original ideas from long-term memory (Benedek et al., 2014) or mere fixation of a fixation cross (Fink et al., 2009a, 2009b). Notably, in a figural divergent thinking task of the Torrance Test of Creative Thinking (Huang et al., 2013), comparison with the generation of non-original ideas showed that the left IFG was also activated (Huang et al., 2013). In the RAT, the left IFG was also more activated during insight trials than during non-insight trials (Jung-Beeman et al., 2004). Interestingly, a meta-analysis on neuroimaging studies of insight (Shen et al., 2018a) provided evidence of an integrated network of insight-activated regions, which includes left IFG, right medial frontal gyrus, the left amygdala, and the right hippocampus. A tDCS study suggests that it may not so much be the degree of activation of left or right IFG that matters in creativity tasks but rather the balance between these two areas. Mayseless and Shamay-Tsoory (2015) have used tDCS to change this balance systematically by comparing a left-IFG-cathodal/right-IFG-anodal montage with the opposite set-up (left-IFG-anodal/right-IFG-cathodal). As predicted, cathodal (deactivating) tDCS over the left, and anodal (activating) tDCS over the right IFG improved divergent-thinking performance in an AUT, whereas the opposite montage or separate stimulation of left and right IFG did not affect performance.

What might be the role of left IFG in creativity tasks? The left IFG is generally thought to be associated with cognitive control, interference resolution, and response selection (Abraham et al., 2012; Benedek et al., 2014; Chrysikou, 2019). More specifically, activation of the left IFG is related to high flexibility scores of the Torrance Test of Creative Thinking (Chávez-Eakle et al., 2007), which implies a link to metacontrol flexibility. Patients with selective lesions in the left IFG were found to make more errors in a task that requires suppressing prepotent manual responses to letter stimuli in a Go/NoGo task (Swick et al., 2008) and on a verb generation task for nouns that had many possible responses, such as ‘cat’, but not for nouns that had few possible responses, such as ‘scissors’ (Thompson-Schill et al., 1998). This pattern fits with the suggestion of Jung-Beeman (2005) that left IFG might be involved in the selection of semantic representations and in inhibiting concepts competing for action or for consciousness. Accordingly, left IFG might combine aspects of persistence—by inhibiting irrelevant thoughts—with aspects of flexibility—by facilitating the search within the pool of relevant thoughts. Evidence has shown that this region presumably mediates the semantic selection in the generation of novel, original ideas, a ubiquitous process in divergent thinking tasks (Seger et al., 2000), and it seems to be particularly sensitive to the influence of semantic distance or associative strength concepts, as weaker associative strength often leads to a stronger BOLD response in this area (Abraham et al., 2012; Bunge et al., 2004; Green et al., 2010).

Of particular interest, the activation patterns of left IFG suggests stronger commonalities between divergent thinking (e.g. as measured with AUT) and insight solutions in the RAT, which both lead to strong activation in this structure (Fink et al., 2009a, 2009b; Jung-Beeman et al., 2004), than between insight solutions and analytical solutions in the RAT, as the former activates the left IFG much more than the latter (Jung-Beeman et al., 2004). However, it is important to keep in mind that all comparisons between divergent and convergent thinking that we consider were obtained with verbal material. Given that the involvement of left IFG seems to depend on the verbal nature of the stimulus material (Boccia et al., 2015), this means that the role we consider for the left IFG might not generalize to other stimulus domains.

The left DLPFC has been associated with cognitive control including executive functioning and working memory (Andrews et al., 2011), and is thought to facilitate creativity by maintaining focused-attention and goals, manipulating information in working memory, and inhibiting task-irrelevant information (Beaty and Schacter, 2018), which is more related to metacontrol persistence. Although the left DLPFC was shown to be activated during the AUT task (Beaty et al., 2015), transcranial direct current stimulation (tDCS) of left DLPFC facilitates convergent thinking performance somewhat more reliably than divergent thinking (Zmigrod et al., 2015). This can be connected back to metacontrol, as persistence, which requires participants to keep on the goal of the task, is related to working memory and the dorsolateral prefrontal cortex (DLPFC) (Curtis and D’Esposito, 2003). Interestingly, cognitive flexibility, which is related to the activation of the left IFG (Chávez-Eakle et al., 2007), has been found to be associated with the deactivation of the DLPFC in patients with bipolar disorder, who performed a simple motor response flexibility task (Nelson et al., 2007).

In conclusion, the left IFG and DLPFC are both active in divergent and convergent thinking, but they seem to have opposite activation dynamics and facilitate different types of creative thinking. The left IFG, which has been found mostly activated (or more strongly activated than right IFG: Mayseless and Shamay-Tsoory, 2015) in divergent-thinking and other cognitive flexibility task, might implement metacontrol flexibility, while the activated left DLPFC might implement persistence, which helps in convergent thinking but hinders in flexibility tasks.

2.4. The right hemisphere

In EEG studies of divergent and convergent thinking, changes in alpha synchronization (Pfurtscheller and Lopes da Silva, 1999) have often been observed. While overall increased alpha synchronization was found during both divergent and convergent thinking tasks (Benedek et al., 2011), alpha synchronization was found to be particularly strong in the right hemisphere during divergent thinking tasks (for a review: Runco and Yoruk, 2014). Specifically, during AUT performance, participants who scored higher on originality showed higher alpha synchronization in the right posterior parietal cortex compared to their lower scoring counterparts (Fink et al., 2009a, 2009b). In line with this, compared with deliberate mind wandering, which requires more cognitive control, participants with higher rates of spontaneous mind wandering, thought to reflect a more flexible state, showed cortical thinning in the regions of the right parietal cortex (Golchert et al., 2017). Taken altogether, this suggests that structural changes in the right parietal cortex might also be an indicator of flexibility.

In the RAT, alpha power in this specific region was also increased in the preparation period of insight trials specifically (Jung-Beeman et al., 2004; Kounios et al., 2006). As discussed above, insight solutions can be suspected to rely more on metacontrol flexibility than analytical solutions, suggesting a close association between right hemisphere alpha synchronization and metacontrol flexibility.

In contrast, tasks with a stronger convergent-thinking component (e.g., intelligence tests of mental arithmetic or reports of the common ending of well-known proverbs), show more alpha *de*synchronization than divergent-thinking tasks (Krug et al., 2003; Mölle et al., 1999;

Shemyakina et al., 2007). In addition, during analytic trials of the RAT (specifically during the preparation period), stronger alpha *de*synchronization in the occipital cortex was found compared than in insight trials (Kounios et al., 2006).

The emerging pattern of stronger alpha synchronization in areas of the right hemisphere during more flexibility-heavy tasks, like divergent thinking or insight solutions in convergent tasks, and alpha *de*synchronization in these structures during persistence-heavy, convergent tasks might seem to be inconsistent with the available evidence from fMRI studies that, as we will see, rather systematically show weaker activation of right-hemisphere structures in flexibility-heavy tasks than in persistence-heavy tasks. But we need to consider that the alpha frequency band is the lowest that the human brain exhibits, which means that entraining neural firing patterns to synchronize at the lowest frequency band possible reduces the average neural activity in the synchronized brain systems. Accordingly, it should not be surprising that the alpha band power synchronization is negatively correlated with BOLD signals in the corresponding brain areas (Scheeringa et al., 2011; Scheeringa et al., 2016). Hence, from the reviewed EEG studies, one would expect lower BOLD activation in right-hemisphere structures in flexibility-heavy tasks than in persistence-heavy tasks.

Indeed, the AUT induced weaker activations in the right than in the left angular gyrus, and this asymmetry was more pronounced than in object characteristic tasks (Fink et al., 2009a, 2009b). The angular gyrus is located in the parietal lobe and close to the superior temporal gyrus (STG), and the weaker activation seen in the right angular gyrus is thus consistent with reported increase of alpha synchronization in the posterior parietal cortex of the right hemisphere as seen in EEG studies (Fink et al., 2009a, 2009b; Kounios et al., 2006). During the preparation period of insight trials in the RAT, the STG also showed stronger activation in the left than the right hemisphere (Kounios et al., 2006). The angular gyrus and the STG are located very close to each other, and are thought of being part of a memory-related network (Chávez-Eakle et al., 2007; Seghier, 2013). In flexibility-heavy creative thinking, areas in the memory-related network of the right hemisphere exhibit a weaker and more diffuse activation state, which is thought to facilitate the (re-) combination of semantic information that is normally distantly related (Jung-Beeman, 2005), which in turn is crucial in AUT performance. Note that this fits the suggestion that alpha synchronization might facilitate the (re-)combination of distantly related semantic associations (Fink et al., 2009a, 2009b). Accordingly, we suggest that metacontrol flexibility is characterized by increased alpha synchronization and weaker BOLD signals in the relevant structures of the right hemisphere. As one would expect from this perspective, convergent thinking was found to be associated with the exact opposite pattern: alpha *de*synchronization and stronger right hemisphere activation. For instance, alpha *de*synchronization has been found during analytic thinking (Kounios et al., 2006). Even more interestingly, the left STG is more strongly activated during the preparation period (during this period participants might be searching for distantly semantic associations in memory) of insight (Kounios et al., 2006), but at the moment when the insight occurs (i.e., when participants find the correct solution in the RAT), the right STG is more strongly activated (Jung-Beeman et al., 2004). This suggests that insight solutions are characterized by a (perhaps spontaneously established) flexibility-biased metacontrol state at the beginning of a trial that turns into a persistence bias produced by the finding of the solution.

In conclusion, the right PPC and/or STG (and sometimes parts of the occipital lobe) seem to be systematically affected by metacontrol policies: tasks or particular intervals of trials that rely on metacontrol flexibility are associated with stronger alpha synchronization and weaker BOLD signals in right-hemispheric brain structures, whereas tasks or intervals that rely on persistence are associated with alpha desynchronization and stronger BOLD signals in right-hemispheric brain structures. Alpha synchronization and weaker BOLD in these structures seem to be associated with a broader scope of the semantic search. As considered by Runco and Yoruk (2014), divergent thinking such as in the AUT might lead the participant to use some superficial representations of the object cue, so that for instance a tin can would be represented by its primary association of being made of tin. This would be represented in the corresponding working-memory structure in the left hemisphere, which in turn would steer the search for secondary semantic or episodic associations, for which structures in the right hemisphere would play an important role (Jung-Beeman, 2005). This search should not be particularly selective but rather broad, and thus benefit from the weak activation of a broader areas (Runco and Yoruk, 2014). As mentioned already, this hypothesis was indeed supported by the observation of stronger alpha synchronization in the right hemisphere in participants who exhibited high originality scores in the AUT (Fink et al., 2007), thought to reflect high flexibility, because the distant or secondary associations, which could help to differentiate an idea from common ideas, might be generated in the right hemisphere.

3. Metacontrol of creative cognition: A neurocognitive framework

Our selective review has revealed that divergent and convergent thinking are associated with systematically different brain activity. Divergent thinking and similar cognitive activities are characterized by a neural activation pattern that consists of strong activation of left IFG (or a bias of the left/right IFG relationship towards the left IFG) associated with weak activation of the left DLPFC and of right-hemispheric structures like PPC and/or STG. If we assume that the left DLPFC codes for the task goal and holds the guiding search template, the left IFG broadens the search within the target domain, and the right PPC/STG controls the grain size of the semantic/episodic memory search, this pattern nicely fits with a flexible metacontrol style in the sense of Hommel's Metacontrol State Model (2015; Hommel and Colzato, 2017a): according to his model, flexible metacontrol is characterized by providing little top-down guidance by representations of the action goal and only weak competition between alternative selection candidates. Convergent thinking, in turn, was found to be characterized by a neural activation pattern that consists of weak activation of left IFG associated with strong activation of both DLPFC and right-hemispheric structures including right PPC and STG. It is easy to see that this pattern nicely fits with a persistent metacontrol style that, according to Hommel's Metacontrol State Model, is characterized by providing strong top-down guidance by goal representations and strong mutual competition between alternative selection candidates.

We thus tentatively conclude that the two observed activation patterns (lIFG+, lDLPC-, rPPC/rSTG-vs. lIFG-, lDLPC+, rPPC/rSTG+) represent examples of metacontrol states that are biased towards flexibility and persistence, respectively (see Fig. 3). Assuming that flexibility and persistence represent the two poles of a continuous metacontrol dimension, we thus assume that the same holds for the observed activation patterns. That is, we speculate that left IFG and DLPFC and corresponding right-hemispheric structures form a neural network that can vary continuously from lIFG+, lDLPC-, rPPC/rSTG-to lIFG-, lDLPC+, rPPC/rSTG+ and, by doing so, serve to implement metacontrol biases of different degrees towards flexibility and persistence, respectively.

Further assumptions will be necessary to capture the observations obtained in insight trials of convergent thinking tasks, however. Remember that such trials reveal a pattern showing strong activations of both left IFG and the left DLPFC (Shen et al., 2018b; Zmigrod et al., 2015), although there is still a trade-off between them (Nelson et al., 2007). Right STG, the memory-related component, showed lower BOLD activation in the preparation period of insight trials, together with stronger alpha synchronization in the right hemisphere (Jung-Beeman et al., 2004; Kounios et al., 2006). However, as soon as the insight actually occurred, the right STG became more strongly activated (Jung-Beeman et al., 2004). From a metacontrol perspective, this scenario would suggest that the metacontrol state can change throughout an insight trial (see Fig. 4): it starts with a mixture of strong DLPFC

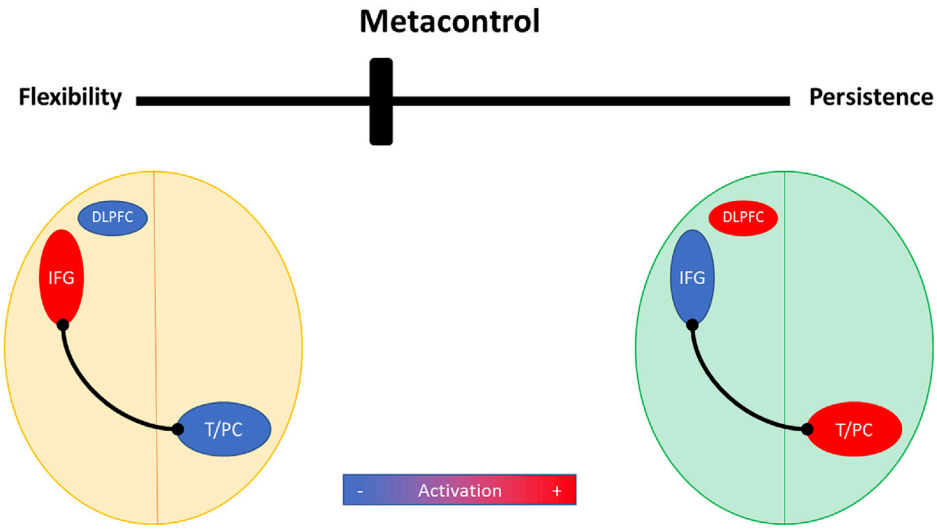

Fig. 3. A proposed neurocognitive framework of the metacontrol of creative cognition. The key idea is that flexibility is promoted by weak activation of the DLPFC and T/PC together with a strongly activated left IFG, whereas persistence would be characterized by the opposite pattern. Note that it may not the absolute activation level of left IFG that matters but rather the balance between left and right IFG (Mayseless and Shamay-Tsoory, 2015).

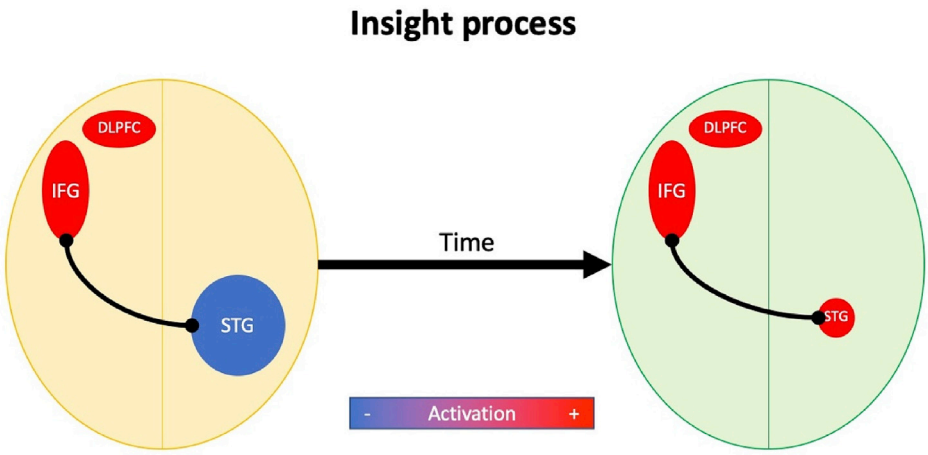

Fig. 4. The metacontrol of insight. During an insight trial of the RAT, the left IFG and the left DLPFC might both be activated, although there is still a trade-off between them, and the activation pattern of the right STG changes throughout time. In the preparation period, the right STG might show a diffused and weaker activation pattern (indicated by the size and color of the area respectively) to facilitate the (re-)combination of the distant or secondary associations. Once insight actually occurs, the right STG would strongly be activated, indicating that the only correct solution is generated with an "Aha" feeling.

involvement, presumably an indicator of multiple-constraints tasks like the RAT (where the search template consists of three words rather than one word), and a strongly activated IFG that indicates a flexibility bias, together with only weakly activated right-hemispheric structures. But once the moment of insight is reached, the state of right-hemispheric structures would rather look like strong persistence, at least with respect to the focus on memory items. In other words, the right-hemispheric structures would tend to "zoom-in" onto the result of the insight. This scenario has a number of suggestions that qualify our tentative approach and identify critical questions that future research needs to address.

First, it implies that the interplay between left IFG and right-hemispheric structures might be more essential for the establishment of flexibility in AUT than the degree to which DLPFC is activated. Comparing Figs. 3 and 4 reveals that the relationship between IFG and right-hemispheric activation is more systematic than the relationship between either of these structures and DLPFC. It is true that the post-insight part of Fig. 4 does not quite fit this description, but for reasons that we spell out below we think that this misfit is only apparent. This less systematic behavior of DLPFC is likely to reflect that the degree to which it is activated during a task depends on its working-memory demands. The activation of DLPFC is known to increase with the number or complexity of the content it needs to hold, that is, on the working-memory demands of the task (Hussein et al., 2014). These demands are clearly higher in the RAT than in the AUT, as the former requires holding three words and their related associations, while the latter requires holding only one word. If, thus, DLPFC involvement increases with the number of cue words, a stronger activation in the RAT may reflect the working-memory demands of this task rather than its convergent nature. For this reason, we speculate that, at least with verbal material, the activation relationship between IFG and right-hemispheric structures is more strongly related than the relationship with DLPFC, which in turn might more depend on task-specific requirements unrelated to meta-control, such as verbal information. However, note that this does not necessarily imply the absence of privileged communication between left DLPFC and right-hemispheric memory-related structures. Gross et al. (2004) used MEG to identify a fronto-parieto-temporal network in an attentional blink task, which—similarly to creativity tasks—required the matching of activated verbal stimuli against a short-term-stored search template. Synchronization analyses revealed particularly strong communication between left frontal regions and right PPC in the beta frequency band, and the strength of this communication predicted successful performance. It is possible that a similar kind of communication is established in creativity tasks, involving the left DLPFC and right-hemispheric memory-related structures, and if this communication is based on neural synchronization, it does not necessarily imply positive

relationships between the BOLD levels of the communicating structures.

Second, our scenario implies that metacontrol states can be changing fast, even within one trial. This fits with recent claims of Mekern et al. (2019b) that adaptive metacontrol may call for the ability of performing rather quick switches between flexibility and persistence—an idea that also fits with the implication of the stage model of creativity suggested by Wallas (1926). The scenario would also suggest that such switches can occur spontaneously or driven by the results of information processing. Studies on insight have revealed that the probability of solving a problem through analytical hypothesis-testing or through insight can be predicted by the preparatory state, the particular metacontrol bias we would argue, but so far it remains unclear when and why participants establish particular preparatory states and why these states vary from trial to trial. This suggests that metacontrol biases can undergo spontaneous drifts, so that different trials are carried out under different flexibility or persistence biases. Further research is needed to identify possible predictors of such drifts, which could be time on task, success in the previous trial, the search duration or difficulty in the previous trial, and more. According to our scenario, changes in metacontrol bias may also be driven by the results of information processing, so that the search for a solution could be broad, facilitated by a flexibility bias, but once a solution is found, stronger persistence could set in to allow for the processing to focus on the respective concept. Again, this would fit with the stage model suggested by Wallas (1926). However, further research is needed to understand whether and how changes in metacontrol states are communicated to the relevant neural systems.

4. Future research

Our framework provides a guide to investigate the similarities and differences of divergent and convergent thinking from a metacontrol perspective, which we feel can help organizing and integrating future research efforts. First, neuroscientific studies, ideally combined with machine learning or similar techniques, could aim to better characterize states of convergent and divergent thinking on the one hand and states of persistence and flexibility on the other, so to validate the idea that thinking styles and metacontrol are related.

Second, this could be done in studies with manipulations that are assumed to induce or promote particular metacontrol styles, such as meditation (Hommel and Colzato, 2017a) or positive and negative affect (Dreisbach and Goschke, 2004) to see whether and how these factors modify metacontrol and thinking styles.

Third, it makes sense to regard our functional characterization of the key players in regulating human creativity as an only intermediate step towards the development of a more mechanistic computational model of creative cognition and the (meta)control thereof (Mekern et al., 2019a). We suspect that cognitive processes can be broken down into more to specific neural computations, which can then be defined in the model as specific parameters. For instance, Mekern et al. (2019b) have suggested that the balance between persistence and flexibility might be determined by a parameter that regulates the degree to which decision-making is controlled by top-down, goal-related settings and the strength of inhibition between alternative choices. This would provide us with a model that can predict behavior on multiple creativity-like tasks—arguably one of the biggest challenges in modern creativity research.

Fourth, the function of the right parietal cortex is still worth being more investigated. In our framework, it might determine, together with the right STG, the size of the search field in long-term memory. But it is important to consider that is adjacent to ECN (anterior inferior parietal cortex) and DN (posterior inferior parietal cortex). As we know, alpha synchronization in this area implies internal attention, but how this is related to different metacontrol state is still unclear.

Finally, it remains an open question whether, and how, norepinephrine is involved in the regulation of human creativity, and whether or how it interacts with dopamine and, possibly, the activities of the right parietal cortex.

5. Conclusion

Taken altogether, we suggest that creative cognition in divergent- and convergent-thinking tasks is modulated by metacontrol states, where divergent thinking and insight solutions in convergent-thinking tasks seem to rely on, or benefit from metacontrol biases towards flexibility, whereas convergent, analytical thinking seems to rely on, or benefit from metacontrol biases towards persistence. The particular metacontrol biases seem to be reflected by particular brain-activation patterns, which, at least in the case of verbal materials, involves the left IFG and right-hemispheric structures like PPC, STG, and/or occipital area. So far, the patterns showed rather systematic across fMRI and EEG studies, but more specific analyses of neural communication in particular frequency bands do not necessarily translate into particular BOLD patterns. We admit that our framework is very tentative and much further research is needed to provide more details, but we do think it can serve as a first proxy to guide such research into the mechanistic details of human creative cognition.

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